impossible to find such a point, but it is still necessary to perform a successful measurement.

For this purpose, this standard describes methods for minimizing errors when measuring asymmetric or swirling flow, provides correction coefficients for certain types of errors, and defines procedures for determination of uncertainty increase in cases where it is not possible to compensate the measurement errors in another way.

Moreover, it provides a basic overview of the most common flow distortions in closed conduits: asymmetric flow velocities distribution occurs if all flow direction changes are in the same plane, whereas the swirling flow requires flow direction changes in two planes to be established.

Unlike the asymmetric flow, the swirling flow has a substantial effect on the reading of Pitot static tubes as well as current meters, and therefore, measurement in such cases should be avoided if possible.

If it is still needed to measure under such conditions, it should be noted that swirling flow lasts much longer than other forms of distortion and the required length for achieving a steady flow is several times higher when compared to other types of unsteady flow.

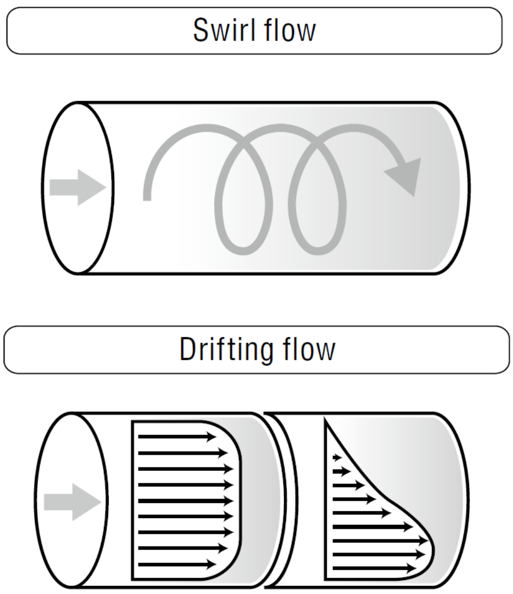


Fig. 1. Swirl flow and drifting flow – basic distortions in closed conduits [3].

5 Practical applications

5.1 A. Beaulieu et al., A flowmeter for unsteady liquid flow measurements

This paper describes a novel instrument for measuring pulsating flow in a special application using the Venturi tube principle (Fig. 2.) Unsteady flow conditions, in this case, are caused by a medical device called a liquid ventilator intended for human emergency external ventilation using a special liquid for O_2 and CO_2 transport. Medical devices for vital functions support are another example of systems working with unsteady (pulsating) fluid flow and thus requiring a proper measurement even under these non-standard conditions.

The proposed solution uses two symmetrical Venturi tubes oriented in opposite directions and equipped with three pressure sensors. As the pulsating stream flows through, the readings of the sensors are taken as inputs for solving a modified unsteady Bernoulli equation describing this system.

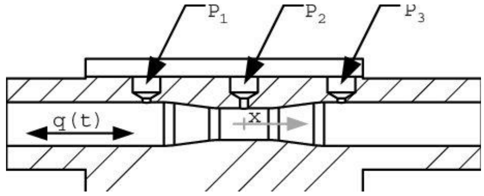


Fig. 2. Venturi tube device with pressure sensors for measurement of pulsating flow in a medical device [4].

5.2 F. Laurantzon, R. Örlü, N. Tillmark, P. H. Alfredsson, Response of common flowmeters to unsteady flow

This paper is focused on an experimental comparison of chosen fluid flow measuring devices investigating a pulsating compressible flow in a closed duct with mass flow rates from 80 to 130 $g \cdot s^{-1}$ for various pulsating frequencies (10 – 80 Hz), i.e., conditions similar to those in combustion engines.

Table 1. Relative deviations of mean mass flow from reference value of 80 g/s of various types of flow measurement devices for given flow pulsation frequencies [5].

Flowmeter	10 Hz	20 Hz	30 Hz	40 Hz
Venturi	1.02	1.06	1.09	1.05
Pitot	0.95	1.04	1.18	1.07
Hot-film	0.98	0.97	1.29	1.89
Vortex	0.98	0.99	1.08	1.01
Turbine	1.24	1.21	1.18	1.07

The significant deviation from the reference value of hot-film probe measurements for frequencies 30 and 40 Hz is notifiable compared to relatively close results for the frequency range 10 – 20 Hz (Table 1.)

5.3 F. Laurantzon, Flow Measuring Techniques in Steady and Pulsating Compressible Flows

This detailed work deals with a complex description of possible measuring techniques for applications with pulsating compressible flow found, e.g., in combustion engines.

Compared to the previously mentioned sources, in this one, another flow measurement technique was applied – thermal anemometry. A device called hot-wire mass flow meter was used to a determination of fluid flow rate in the pipes of the experimental set-up. When compared to a reference flow meter, it proved to be suitable for this purpose with a maximum relative deviation of ± 3 % (Table 2. and Fig. 3.)

A measuring sensor based on a hot-film probe was then used for the analysis of the pulsating flow with ambiguous results due to its inability to identify the backflow stream.

Table 2. Relative deviations of mean mass flow measured by hot-wire probe from reference value for given flow pulsation frequencies [6].

$\dot{m}$	$f_p = 0$ Hz	$f_p = 40$ Hz	$f_p = 60$ Hz	$f_p = 80$ Hz
80 g/s	1.01	0.997	1.01	-
130 g/s	0.968	0.979	0.988	1.02

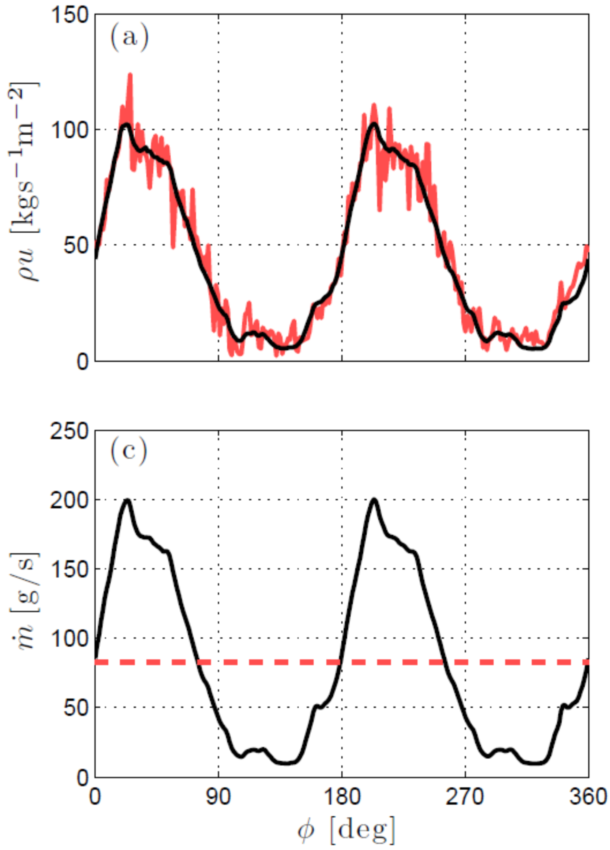


Fig. 3. Resulting mass flow rate measurements by hot-wire method (varying solid line, top chart) compared with phased averaged value (bold black solid line, both charts) and integrated mass flow rate (dashed line, bottom chart) for various pulse phases (horizontal axis) [6].

5.4 M. Kurth, P. Komp, Influence of installation and operating conditions on the measurement of high-pressure natural fluid flow, ultrasonic flow meters (in Czech)

The authors are focusing on flow measurement using ultrasonic flow meters in natural gas pipelines, i.e., closed circular ducts with large diameters and high pressures. Motivations for investigation of unsteady flow measurement are obvious – in the real pipelines, it is hard to find a place with the steady flow, but the measurement is still necessary. Lengths of about 28 diameters before and 13 diameters after the measurement point are mostly required for fluid flow stabilization in this field. Therefore, physical devices for a faster flow stabilization already mentioned, e.g., in ISO 7194, are widely used (Fig. 4.)

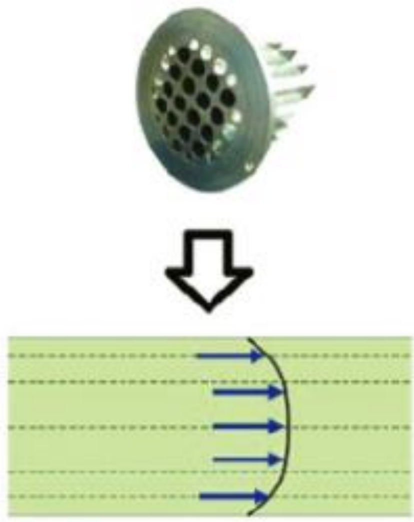


Fig. 4. Zanker-type flow conditioning plate used for fluid flow stabilization in natural gas pipelines [7].

As another solution, the authors are considering ultrasonic measurement in more planes or directions to overcome the errors caused by the unsteady flow and swirling (Fig. 5.)

Each of the presented configurations has its own advantages, drawbacks, and field of utilization. Generally, arrangements with more layers of ultrasonic probes produce a better approximation of the velocity profile, whereas configurations with one or more reflections succeed in better compensating both the symmetric and asymmetric swirls.

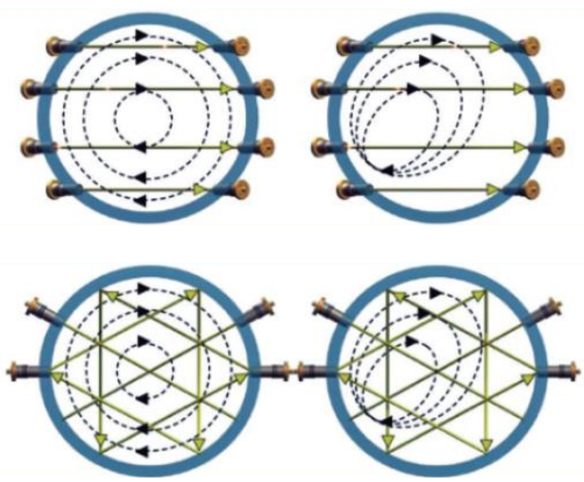
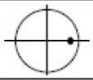
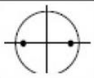
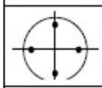
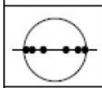
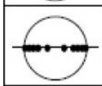
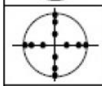
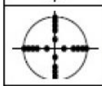


Fig. 5. Various configurations of ultrasonic flow meters with shown signal paths for compensation of symmetric and asymmetric swirls during measurement in natural gas pipelines [7].

5.5 I. Caré, F. Bonthoux, J.R. Fontaine, Measurement of air flow in duct by velocity measurements

In this paper, experiments with unsteady fluid flow in a circular air duct with a diameter of 200 mm are described. The measurement was performed behind a flow distortion in the form of a 90° bend; the measuring device used was a Pitot static probe.

Table 3. Relative maximum error for various configurations of measuring points and distance from the source of the flow distortion [8].

	E: maximum error in %							
	k	p	k*p	*L/D*				
				2	**4**	**6**	**10**	**20**
	1	1	1	47	29	22	15	9
	1	2	2	25	16	12	8	5
	2	2	4	13	8	6	4	3
	1	6	6	11	7	5	4	2
	1	10	10	9	5	4	3	2
	2	6	12	6	3	3	2	1
	2	10	20	4	3	2	1	1

During the experiment, flow conditions defined with Re > $2 \cdot 10^5$ were investigated. The method used for the compensation of increased measurement uncertainty due to the unsteady flow caused by the bend was based on an increased number of measurement points for a better approximation of the velocity profile. The results obtained are shown in the Table 3. As can be seen, a maximum error of 4 % can be achieved even in a very short distance from the bend (L/D = 2, where L is the distance between the probe and the bend, D is the diameter of the air duct) if we use 20 measurement points across the air duct diameter in two directions.

6 Conclusion

The general methodology for measuring fluid flow in closed profiles is defined, for example, by the relevant standards EN 14277 [1] and ISO 7194 [2]. In both documents, a sufficient distance of the measuring point from the sources of instability is required, which corresponds to several hydraulic diameters of the given pipeline.

The measurement under unstable conditions has some specific applications in natural gas supply or in pumping liquids, e.g., [7] and [4], respectively. A detailed description of the properties of measuring methods and instruments appropriate for the analysis of unsteady fluid flow is presented in [5] and [6]; among other things, an acceptable accuracy of thermal anemometric probes for a given purpose is documented here.

The key document for the specified purpose is [8]. In this work, the experiment performed deals with a ventilation air duct, and the first usable results are presented.

The presented measurements were taken with Pitot static tubes in a circular air duct with a diameter of 200 mm and for a Reynolds number of about 200,000, which corresponds to relatively high air velocities compared to typical values. The results show an acceptable relative error of 4 % even for measurements very close to the source of flow distortion (L/D = 2).

Based on the statements above, the research task can be specified in the following way: the measurement will be performed by hot-wire probes behind the 90° elbow bend in air ducts with a diameter of 300 - 400 mm, at air flow velocities from 0.5 to 5 $m \cdot s^{-1}$ (typical velocities in ventilation air ducts). Particle Image Velocimetry (PIV) visualization will be used to determine the most suitable places for measurement.

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